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A brief status on condition monitoring and fault diagnosis in wind energy conversion systems

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ABSTRACT

There is a constant need for the reduction of operational and maintenance costs of Wind Energy Conversion Systems (WECSs). The most efficient way of reducing these costs would be to continuously monitor the condition of these systems. This allows for early detection of the degeneration of the generator health, facilitating a proactive response, minimizing downtime, and maximizing productivity. Wind generators are also inaccessible since they are situated on extremely high towers, which are normally 20 m or more in height. There are also plans to increase the number of offshore sites increasing the need for a remote means of WECS monitoring that eliminates some of the difficulties faced due to accessibility problems. Therefore and due to the importance of condition monitoring and fault diagnosis in WECS (blades, drive trains, and generators), and keeping in mind the need for future research, this paper is intended as a brief status describing different types of faults, their generated signatures, and their diagnostic schemes.

Contents

1. Introduction

Wind energy conversion is the fastest-growing energy source among the new power generation sources in the world and this trend should endure for some time. At the end of 2006, the total United States wind energy capacity had grown to 11,603-MW, or enough to provide the electrical energy needs of more than 2.9 million American homes. Wind capacity in the United States and in Europe has grown at a rate of 20–30% per year over the past decade (Fig. 1). Despite this rapid growth, wind currently provides less than 1% of total electricity consumption in the United States. The vision of the wind industry in the United States and in Europe is to increase wind fraction of the electrical energy mix to more than 20% within the next two decades [1].

Harnessing wind energy for electric power generation is an area of research interest and nowadays the emphasis is given to the cost-effective utilization of this energy aiming at quality and reliability in the electricity delivery. During the last two decades wind turbines sizes have been developed from 20-kW to 5-MW, while even larger wind turbines are being designed. Larger sizes

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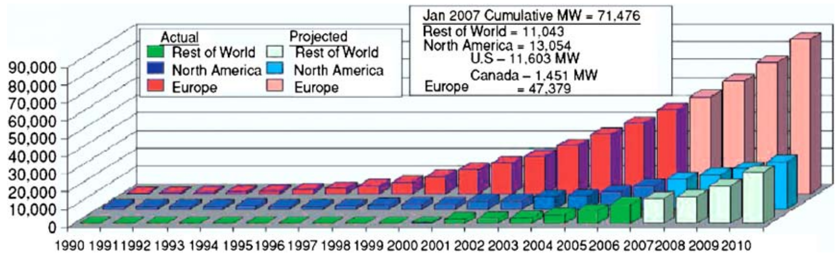


Fig. 1. Worldwide growth of wind energy installed capacity [1].



Fig. 2. Currently largest onshore wind turbine and offshore installations [8].

are physically possible; however, logistical constraints of transporting the components and obtaining cranes large enough to lift the components are potential barriers. Moreover, a lot of different concepts have been developed and tested [2].

Autonomous online condition monitoring systems with integrated fault detection algorithms allow early warnings of mechanical and electrical faults to prevent major component failures.

Side effects on other components can be reduced significantly. Many faults can be detected while the defective component is still operational. Thus, necessary repair actions can be planned in time and need not to be taken immediately. This is important as Wind Energy Conversion System (WECS) generators are inaccessible since they are situated on extremely high towers, which are normally 20 m or more in height (Fig. 2). It is also important especially for offshore plants, where bad weather conditions (storms, high tides, etc.) can prevent any repair actions for several weeks (Fig. 2). Moreover, condition monitoring will also detect extreme external conditions, such as icing or water induced tower oscillations of offshore plants, and can trigger appropriate control actions to prevent damage of plants components. This way, overall maintenance costs and downtime of wind energy converters can be significantly reduced [3–7].

Therefore and due to the importance of condition monitoring and fault diagnosis in WECS (blades, drive trains, and generators), and keeping in mind the need for future research, this paper is intended as a brief status based on an exhaustive review of the state of the art, describing different types of faults, their generated signatures, and their diagnostic schemes. As the Doubly-Fed Induction Generator (DFIG) is one of the most used WECS configurations, the review will be mainly focused on it (Fig. 3).

2. Failure mode analysis

Real wind turbine failure data quantitative analyses have shown important features of failure rate values and trends [9–12].

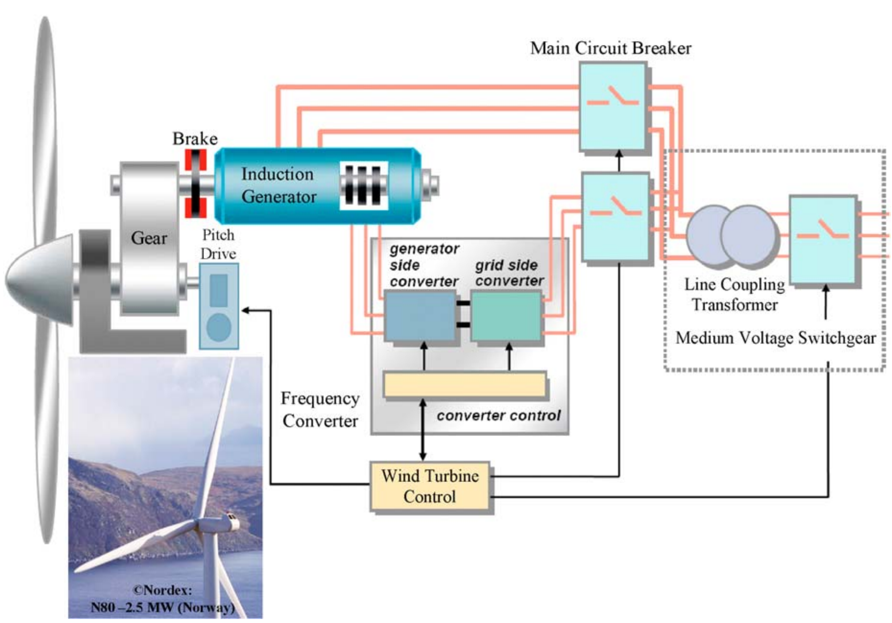


Fig. 3. Most used WECS configuration (with DFIG arrangement) [8].

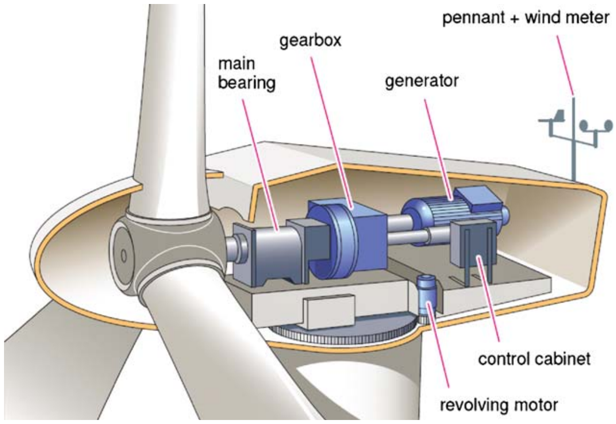


Fig. 4. Wind turbine nacelle cross-section.

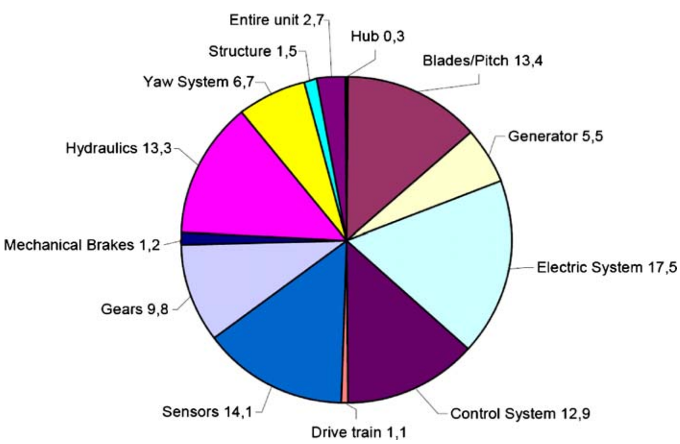


Fig. 5. Failures number distribution [%] for Swedish wind power plants [9].

For illustration, Fig. 4 shows the main wind turbine components that are concerned by the above failure analyses.

In the first study concerning Swedish wind power plants [9,10], it has been shown that most failures were linked to the electric system followed by sensors, and blades/pitch components. This is clearly illustrated by Fig. 5 that shows failure number distribution for Swedish wind power plants that occurred between 2000 and 2004.

Another study, concerning Danish and German wind power plants [11], shows the same tendency. Indeed, principal contributors to the higher German failure rate are the electrical control or system subassemblies (grid or electrical system, yaw system and mechanical or pitch control system) rather than mechanical subassemblies such as the gearbox.

Fig. 6 shows the failure rate in the two power plants during the period 1994–2004.

All the above analyses are consistent with the introduction of variable speed drive technology but are contrary to the received wisdom that gearboxes are a major cause of turbine failure [13].

For the above reasons, the proposed review will be focused on these types of failure.

3. Condition monitoring and diagnosis

It is well known that many electrical and mechanical faults in induction motors have a direct impact on the motor magnetic field. Indeed, they modulate it [14]. Moreover, it has been proven that failures in a mechanical drive train connected to an induction machine can be detected at the terminal of the machine [15].

In the case of wind turbine condition monitoring, a number of published works are based on the following hypothesis: *It is possible to detect wind turbine drive train faults through the terminals of the associated generator* [16,17].

The basic configuration that is used for WECS condition monitoring and diagnosis is shown by Fig. 7. It should be noticed that in modern wind turbines, some signals, such as rotational

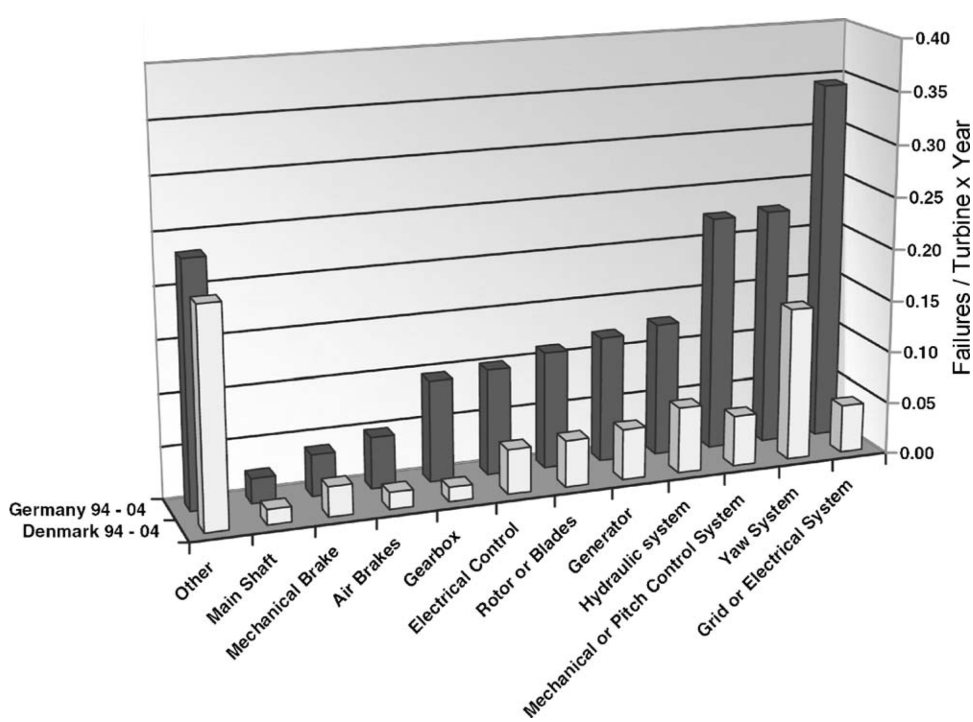


Fig. 6. Failure rates for Danish and German wind power plants [11].

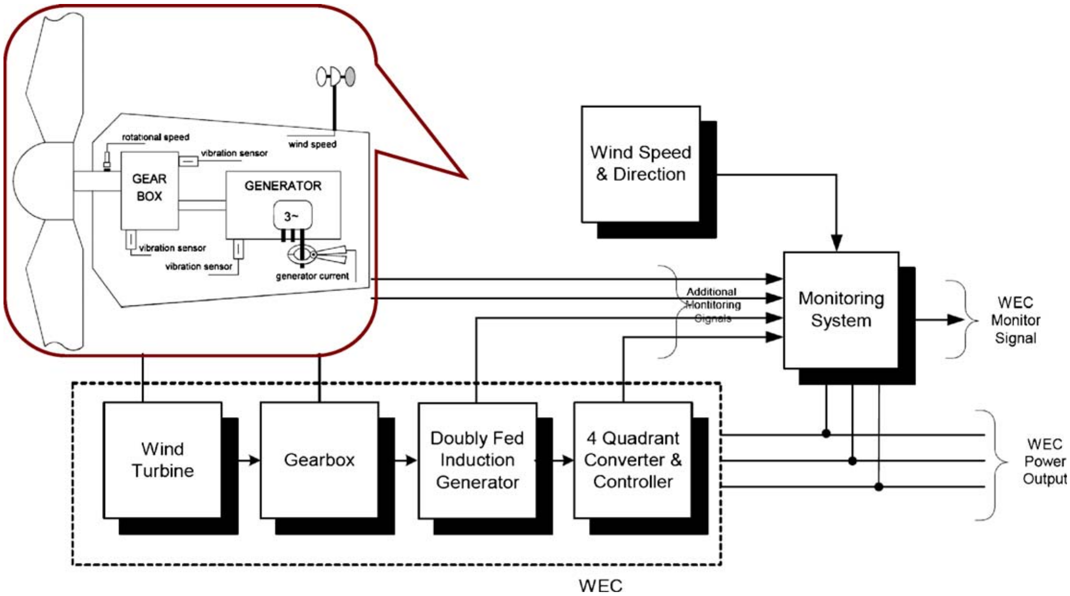


Fig. 7. Basic architecture of WECS condition monitoring and diagnosis [5].

speed, generator temperature, etc., are commonly monitored by the supervisory control system [5].

3.1. Electrical system (DFIG) condition monitoring

There are many techniques and tools available, which are used to monitor the condition of induction machines.

Some of the technologies used for monitoring include sensors, which may measure speed, output torque, vibrations, temperature, flux densities, etc. These sensors are together coupled with algorithms and architectures, which allow for efficient monitoring of the machines condition [18]. The most popular methods of induction machine condition monitoring utilize the steady-state spectral components of the stator quantities. These stator spectral components can include voltage, current, and power and are used to detect turn faults, broken rotor bars, bearing failures and air gap eccentricities [19,20].

The above techniques that are based on steady-state analysis are being applied to induction generators. When scanning the available literature, it has been found that fault detection and diagnosis techniques are mainly arranged for inter-turn stator faults and stator or rotor asymmetries [21–25]. In all these works, authors are just applying well-established techniques to induction generators. However, in refs. [21,22], the authors are using the rotor modulating signals spectra as a diagnosis index for stator and rotor fault characterization. Indeed, the rotor modulating signals have harmonic content that gives evidence of stator and rotor asymmetries more clearly than the harmonic content of stator and rotor currents.

In ref. [26], authors have raised a key feature of wind turbine generator operations. Indeed, they are predominantly transient, therefore prompting the use of nonstationary techniques for fault detection [27]. In this case, wavelet analysis has been used for the detection of stator turn faults in a DFIG. The detection algorithm is a combination of the Extended Park Vector, wavelet analysis, and statistics. This technique was not affected by changes in DFIG speed, which is crucial in WECS applications.

One of the preferred options at present, for large turbines in excess of 2-MW rating, is the variable speed DFIG with the rotor converter connected to the rotor via slip rings [8,28]. However, in contrast to squirrel cage generators there are additional wear parts, e.g. the slip ring system (Fig. 8). Therefore, in ref. [29], the authors are suggesting a patented diagnostic technique for the monitoring of the transmission properties and sparking of DFIG with slip rings. In this case, modifications in the transmission properties are diagnosed using the monitored rotor currents through FFT analysis.

3.2. Damage detection of WECS blades

Wind turbine blades are a vital component. Due to external conditions and internal stress as well as fatigue, the crack and damage may gradually take place as time goes by, thus leading to performance deterioration of wind generation. In other words, it is crucial to monitor the turbine blades so that operation performance can be better ensured. It should be possible to retrofit a condition-monitoring package onto existing wind turbines without requiring additional sensors and wiring on the machine. Therefore, in ref. [30], the authors used the above-mentioned hypothesis to detect the presence of unbalance and defects in the blades of a small wind turbine by measuring the power spectrum density at the generator terminals. In this case, bicoherence, a normalized bispectrum, is used. Indeed, it is able to monitor small physical changes in the machine using a very noisy signal. This technique overcomes problems of the bispectrum which is not convenient for detection purposes [20].

The advantage of such an approach is that the generator terminal quantities are easily accessible during operation, the current via a current transformer, the voltage via a voltage transformer and the power by computation. This is a very useful

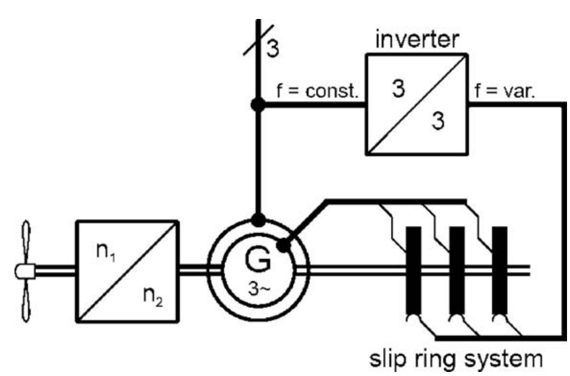


Fig. 8. Slip ring generator system principle.

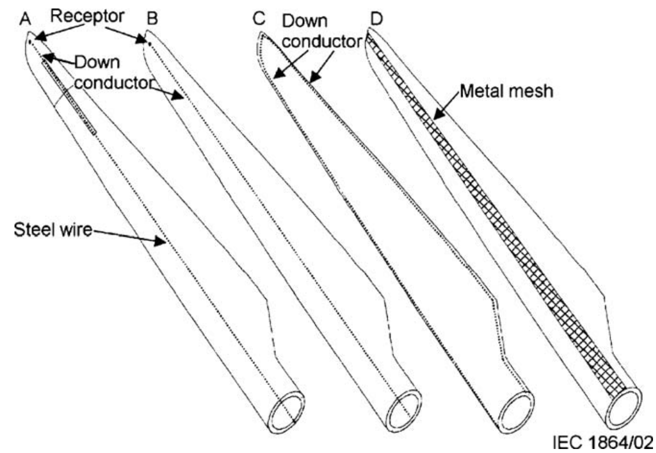


Fig. 9. Lightning protection for large modern wind turbine blades [33].

technique as it requires no additional sensors, particularly on the blades, which is the case in ref. [31], where a continuous wavelet transform-based approach is used to detect blade damage.

Unfortunately, wind turbine blades experience faults and damages that could not be monitored using the wind turbine generator terminals. They are particularly exposed to a major threat from lightning strikes. To prevent damage, blades are equipped with a lightning protection system, like most modern WECS [32] (Fig. 9). However, as lightning is random in nature, a complete protection against its damage is not achievable. Therefore in ref. [33], a method for lightning impact localization and classification using a fiber optic current sensor network that helps to detect damages caused by lightning and to monitor the blades is presented. The system is connected to the wind turbine control and monitoring system.

3.3. Other drive train component monitoring and diagnosis

Other wind turbine key components are roller bearings and gears. For these types of component condition monitoring and diagnoses, the use of the wind turbine generator terminals has not been explicitly investigated. Indeed, in ref. [34] the authors dealt with the demodulation of the current signal of an induction motor driving a multistage gearbox for its fault detection.

In this case, amplitude demodulation and frequency demodulation are applied to the induction motor current to detect the rotating shaft frequencies. A discrete wavelet transform is applied to the demodulated current signal for denoising and removing the intervening neighboring features. Spectrum of a particular level is used for gear fault detection. This technique seems to be very interesting to monitor WECS gearbox as it involves a nonstationary technique.

In the case of rolling bearing fault diagnosis and apart from the well-established techniques developed for induction motor drives [19], a recently published paper seems to be convenient for wind turbine bearing fault detection [35]. Indeed, it uses the wind turbine generator stator current. Moreover, due to the nonstationary nature of this current, the wavelet packet transform provides better analysis under varying load condi-

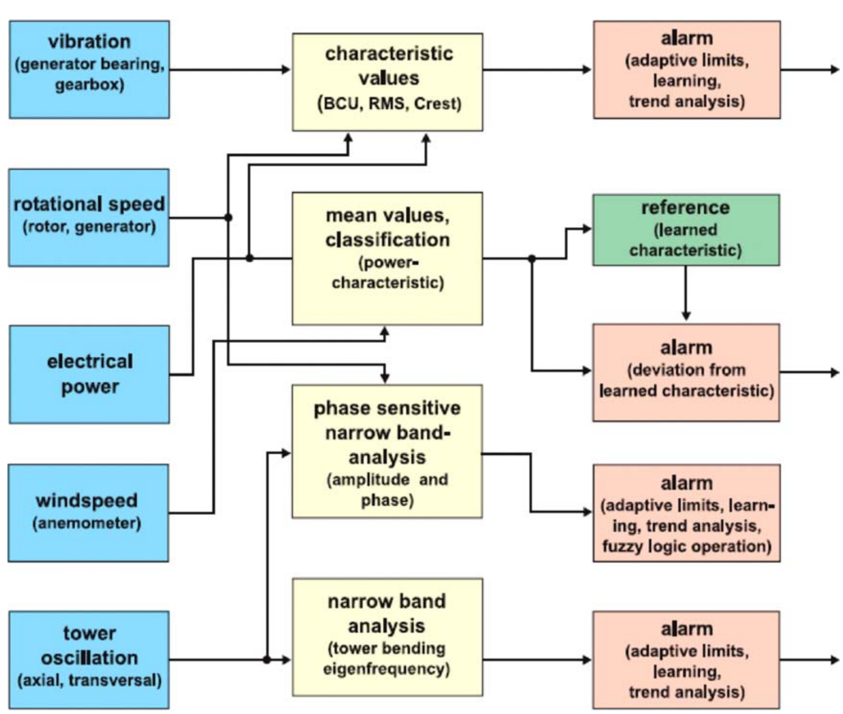


Fig. 10. Bases for WECS condition monitoring and diagnosis [36].

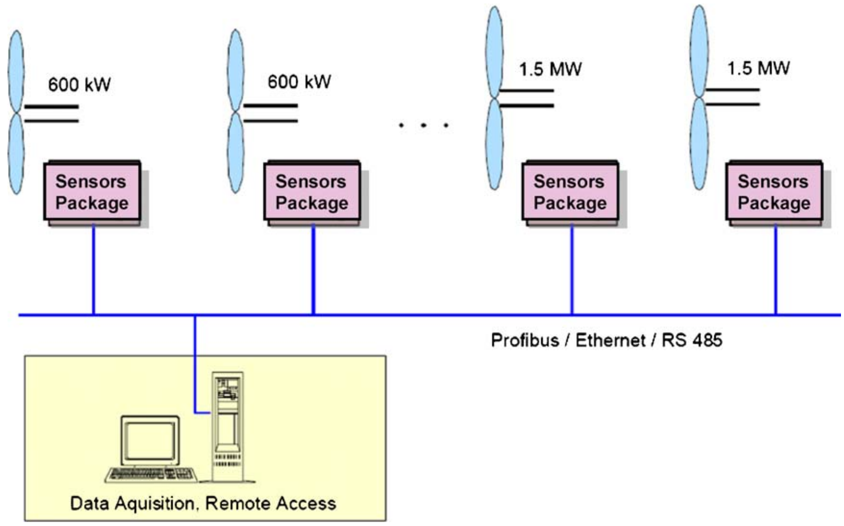


Fig. 11. Condition monitoring network in wind farms.

tions. The wavelet packet transform also permits the tailoring of the frequency bands to cover the range of bearing fault induced frequencies resulting from rotor speed variations (e.g. variable speed DFIG).

3.4. Other fault detection and diagnosis approaches

In ref. [36], the authors propose the application of artificial intelligence techniques for WECS condition monitoring, including the tower, nacelle, and power train. This approach requires a learning process for each individual WECS, and seeks to detect trends, without necessarily linking cause to fault effects. In this case, the proposed approach for WECS monitoring is shown by Fig. 10, where the layer, called evaluation or diagnosis uses neural networks for characteristics learning or fuzzy techniques to combine information from different measurements.

3.5. Data collection

Today, most turbines are fitted with equipment that makes it possible to collect condition-monitoring data remotely via modem or Internet. Moreover, since wind turbines are typically built in onshore or offshore wind farm configurations, there is a need to build up networks (Fig. 11).

With this network approach, fault diagnosis will be optimized comparing WECS operation under identical conditions. Moreover, redundant measurements provided by the wind farm (e.g. wind speed) will be used to improve the overall wind farm performance by minimizing operational losses due to anemometer failures [7,36].

4. Industry applications

Condition monitoring is a machine maintenance tool (known as Condition Monitoring System—CMS) that is becoming a component of long-term service packages provided by some wind turbine manufacturers. Fig. 12 illustrates the integration of a CMS in a WECS [37,38]. In this case, the CMS monitoring functions are based on robust sensor equipment. A typical sensor configuration is shown by Fig. 13: Sensor (1) is an inductive distance sensor to measure the absolute rotor position; Sensors (2)–(4) are static accelerometers to measure the nacelle oscillation in axial and transverse direction, related to the rotor axis; Sensors (5) and (6)

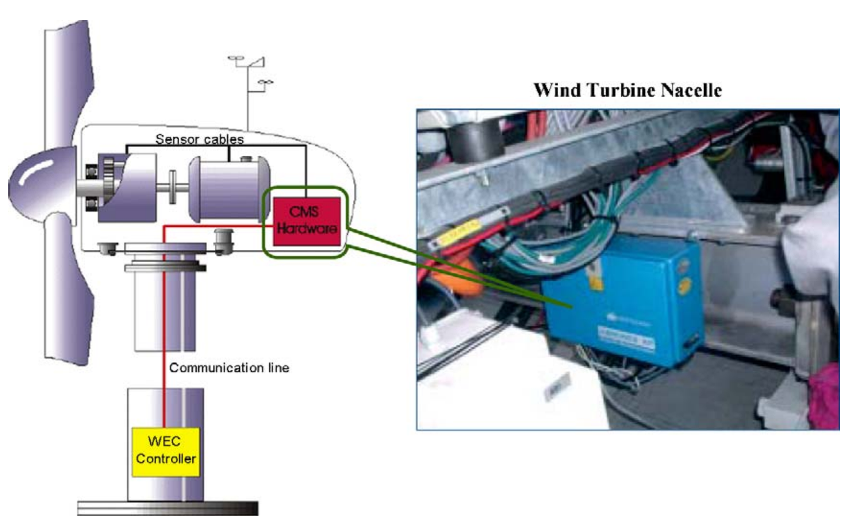


Fig. 12. Integration of a CMS in a WECS [37].

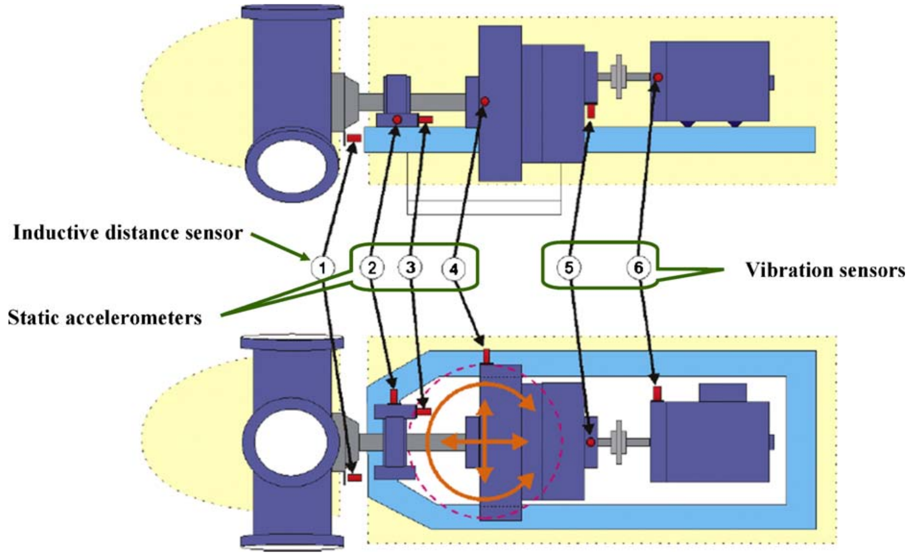


Fig. 13. Typical sensor position [37].

are vibration sensors to measure the vibration induced by bearings and gearwheels.

5. Summary

This paper has briefly reviewed state of art of wind energy conversion systems' condition monitoring and diagnosis. The emphasis has been put on faults that could be monitored using wind turbine generator (DFIG) terminals in an attempt to use well-established techniques developed for induction motors. Indeed, it seems that it is possible to detect wind turbine drive train faults through the terminals of the associated generator. In this context, it has been found that unbalance and defects in small wind turbine blades can be diagnosed by measuring the power spectrum density at the generator terminals. This was also the case of WECS gearbox. However, as wind turbine generator operations are predominantly transient, the use of nonstationary techniques is required for fault detection.

Finally industry application of condition monitoring has been briefly introduced through CMS.

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